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Contract MDA903-76-C-0241
ARPA Order No. 3200
for the Period October 1, 1976
to March 30, 1977
Report Date March 1977

COMPUTER-BASED SUPERVISORY SYSTEM FOR MANAGING INFORMATION FLOW IN C3 SYSTEMS: PACING MODEL

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Prepared For:

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes progress on work centered on the demonstration of a system of integrated on-line adaptive user models designed to automatically select and pace information in a simulated command, control, and communication (C3) system. The report includes: (1) a human-factors based rationale for improving information flow in C3 systems; (2) a description of modifications made to the Tactical and Negotiations Game (TNG) scenario to create a C3 decision simulation in which automatic selection and pacing of

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information can be realistically accomplished; (3) the conceptual specification of a real-time, computer-based model for automatically adapting message pacing rate to the information processing and decision making capabilities of an individual operator; (4) an overview of the software configuration being implemented to support the system. The next phase of work will focus on the system implementation of the newly developed configuration of information selection and pacing models.

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1. SUMMARY

1.1 Report Period

The first two quarters of contract activity involved: analysis of relevant literature; analysis of task requirements; conceptualization and development of system components and configuration; and software development. The following specific tasks were accomplished during the report period.

(1) System design principles were derived from a review of psychological literature relating information pacing and load to human performance and these were applied to system development.

(2) A task requirements analysis was conducted, and the Tactical and Negotiations Game (TNG) was selected and modeled as the C3 scenario for demonstrating a system to select and pace information.

(3) System components and models were designed, the central ones being the message pacing model and the multi-attribute information utility model, and their interactions were configured; in addition, their dependencies upon a self-selection, self-paced operator calibration phase were determined.

(4) As part of the pacing model, a secondary task was selected and designed which requires the operator to make paired-comparison preference choices between two potentially available messages on the basis of header information.

(5) A paired comparison adaptive technique for training the adaptive information selection model was developed and simulated (to determine convergence characteristics and sensitivity) by an interactive FORTRAN program.

(6) A detailed system design was completed which includes a program design language (PDL) description of the principal system modules and their operation, logical specifications for the system's file and data structures, and the design of standard display formats.

1.2 Next Period

The contract activity during the next quarter will primarily concentrate on the system implementation of the newly developed configuration of information selection and pacing models. In addition, the evaluation of system operation will be planned. The specific items of work for the next period include:

(1) Code and test detailed software design and implement on PDP-11/45 computer system; design and code display software to monitor and control operator's station.

(2) Adapt and transfer TNG scenario for interactive play on computer system.

(3) Conduct simulations and manual run-throughs in order to specify initial parameters and procedures related to the primary (TNG) and secondary tasks.

(4) Plan test and evaluation of system performance from operator calibration sessions through the fully automated information selection and pacing mode.

1.3 Program Milestones

The milestone chart for the contract program is shown in Figure 1-1, with the report period illustrated as the shaded portion.

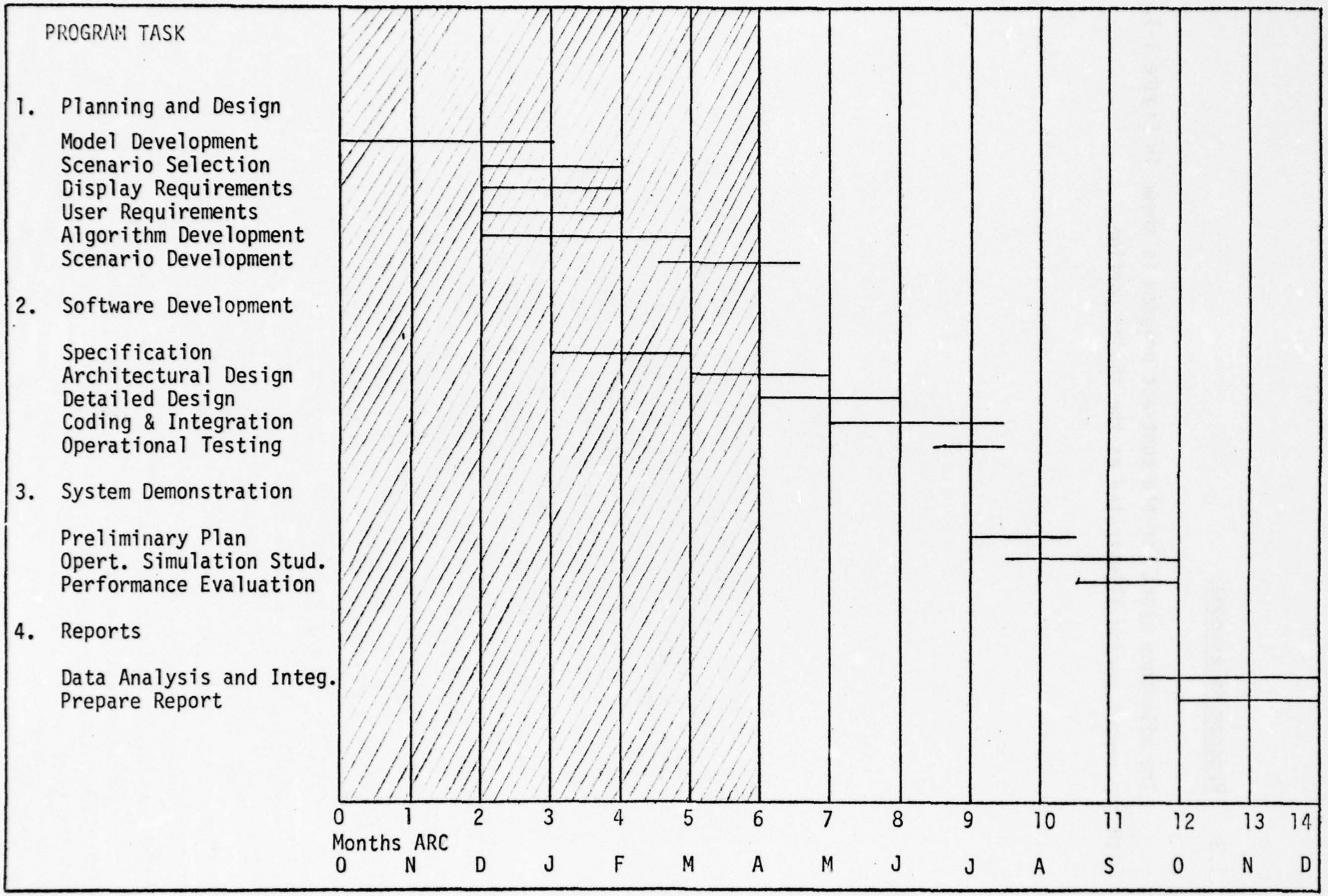

FIGURE 1-1. PROGRAM MILESTONES

2. PROGRAM OVERVIEW

2.1 Statement of Problem

Technical advances have led to increased speed, mobility, and destructive power of military operations. Consequently, the amount and rate of military-information acquisition must also increase. For commanders to make tectical decisions responsive to the rapidly changing succession of events requires information to be processed more efficiently and more effectively than ever before. To meet this need, new computer-based command, control, and communication (C3) systems are being developed and implemented. These systems will aid in the collection, processing (e.g., storage and communication, analysis, and interpretation), and utilization of different types and amounts of military data. The overall process is cyclic -- as information is being used other information is being processed, and new information is being sought and collected. The dynamics of information flow are, therefore, of critical importance and must be constantly monitored and directed.

The consensus concerning current computer-based military systems for C3 operations is that they have increased the rate and density of information flow to such an extent as to overwhelm a commander and his staff. Human factors research is necessary to determine how to control information flow so as to best match the machine capability with the human function in the man-computer interaction. In particular, the programmable features of the computer system should be exploited so that the behavioral dimensions of information flow, such as routing, sequencing, pacing, etc., can be monitored and maintained in a mix optimal for command decision making.

2.2 Rationale

Future C3 systems will be characterized by an increasing emphasis on the man/computer interaction. Experience and experiment have shown that the most cost-effective computer systems are those which most closely match the requirements of their users. Accordingly, a major goal of future C3 system design will be to provide individualized organization and management of dynamic information flow. The purpose of the research undertaken here is to investigate and evaluate means by which computer-based models of the individual user can be used to provide the critical function of *information control*. This would allow each user to obtain consistently information that is both relevant and timely with regard to his individual processing characteristics and immediate decision making needs. Such an aid would substantially improve system effectiveness by increasing the efficiency of information selection and presentation.

2.3 Objectives

The goal of the research program addressed in this progress report is to demonstrate and evaluate system-controlled pacing of automatically selected information in a complex C3 environment. The specific objectives of the current program include the following:

(1) Determine design principles and algorithms for the dynamic computer control of information pacing in C3 systems.

(2) Develop and implement a prototype adaptive (individualized) information pacing system.

(3) Demonstrate and evaluate system-controlled pacing of automatically selected information in a complex, realistic C3 scenario.

(4) Establish guidelines for application of integrated information selection and pacing models to higher level multi-man C3 systems.

The following sections review work conducted under objectives (1) and (2).

2.4 Technical Approach

Progress on this program can be summarized here with regard to the technical approach used in accomplishing the objectives. The first year of contract effort demonstrated the capability of an on-line adaptive model for automatically selecting information in a C3 system. The results of this effort are abstracted below as a preface to an overview of the information pacing system currently being developed during this second year of contract work.

2.4.1 Information Selection Model.

Based on a multi-attribute decompositon of information messages, the adaptive multi-attribute information utility model selects information for an individual user according to his observed information preferences in response to specific situational requirements. An additional algorithm reduces the size of a selected information set by dynamically pruning relatively low-utility items. The model was implemented for a simulated ASW tracking task, and was systematically evaluated in terms of both its intrinsic performance and the performance of an expert operator working with it. The results demonstrated the capability of the model to adapt to varied information-seeking strategies, and to subsequently automate the selection of information appropriate to those strategies. Empirical evaluations showed that an operator was able to perform the tracking task successfully and much more rapidly with automatic selection of information. Moreover, performance effectiveness was enhanced by the removal of messages which contributed little to the overall utility of an information set. These findings add support to the rationale for applying an adaptive approach, based on multi-attribute information utility, for improving information routing and communication in a multi-man C3 system.

2.4.2 Information Pacing Model. The pacing model described in this progress report is designed to display one message at a time. The model is based on the implementation of a secondary task to dynamically assess the operator's load on the primary C3 information processing task. An adaptive algorithm adjusts the baseline pacing rate for a task epoch in accordance with the difference in the previous epoch between the actual level of secondary performance and some desired standard or threshold level. In addition, the display time for each specific message is adjusted with respect to a regression equation which predicts, from a set of predetermined pacing attributes, its required deviation from an overall average message display time. Model-parameter values are determined in a sequence of operator calibration sessions; for example, the standard level of secondary performance is set at the level which is empirically observed, on the average, to be accompanied by the best level of primary task performance.

The individual-based pacing model is being integrated with the previously demonstrated adaptive multi-attribute information utility model of individual information preferences and needs. In combination, the configuration of models determine what new information should be supplied to the operator and when it should be supplied. In fact, the pacing and preference models are logically interconnected through the secondary task, which involves paired-comparison choices between headers of available information messages. The rate of decision performance on this task is pivotal to the pacing model, while at the same time, the actual choices serve the important additional function of training the adaptive information-selection model and keeping it tuned to momentary changes in information preferences.

3. SCENARIO AND TASK DEVELOPMENT

3.1 Scenario Selection

The generalized information selection model and the new pacing model are being implemented into a C3 sceanrio based on the Tactical and Negotiations Game (TNG). A need has existed for a controllable, standard scenario which would serve as a basis for comparing decision aiding systems. The TNG has been recommended as such a common vehicle by reviewers of decision aiding reserach (Slovic, Fischhoff, and Lichtenstein, 1977). This scenario was selected because it possesses realistic task complexity and provides results with applications to real-world decision making. The scenario requires players to process information messages and make decision assessments concerning the military, intelligence, negotiation, and economic activity of a small underdeveloped nation plagued by an internal revolution and foreign intervention.

The TNG involves multi-dimensional information (supported by a backdrop map of the geographical area of concern) for multi-faceted C3 decision making, and it has been repeatedly demonstrated in past research to maintain high subject motivation and produce reliable results. The game may be played by an individual or by groups, with team competition possible. It provides a standard structure or background, but is is flexible in that the situational environment and the particular messages generated and received may be modified. Furthermore, a large body of TNG performance data collected under laboratory conditions where information flow has been handled manually can be drawn upon to comparatively evaluate an automated information-management aid.

3.2 Scenario Development

3.2.1 Performance Measurement. One of the difficulties faced by research users of the TNG has been the lack of a ground truth base for evaluating the quality of the players' decision performance. To overcome this problem, Perceptronics -- as part of our current work effort -- has performed a content analysis on written decision protocols generated in response to a large set of fixed messages during game-playing sessions by many groups of subjects. The output of this analysis is a set of four plausible specific states of the world (i.e., enemy strategies) for each situational content area (military, intelligence, negotiation, economic), with one alternative in each case clearly indicated by a consensus of player opinion as the correct one, i.e., the "school solution". This ground-truth base together with the computerization of the TNG is expected to greatly increase its general useability as a research tool, especially for the study of complex C3-related decision processes.

3.2.2 Content Analysis. An effort was undertaken to establish the consensus of opinion among players of the TNG to the "true" state of the game environment as derived from a given set of messages they received while playing the game. The analysis was based on data obtained by O'Connell (1974) from 48 college students in military officer training programs who played the game in 16 three-man teams. Over the course of game play each group received 64 detailed textual messages, in random order, dealing equally with the military, intelligence, economic and negotiation situation, each represented in about one-quarter of the messages.

As part of the experimental protocol, the groups were given response sheets at the end of the game and instructed to list any possible strategies that they thought the opposing side appeared to be pursuing to achieve their military, intelligence, economic, and negotiation goals.

After listing a set of strategies within each area, they were required to indicate the number of chances out of 100 that the opposing side was following each strategy, with the total adding to 100.

The messages employed by O'Connell were originally created on the basis that they be meaningful to the subjects no matter when during the game they were introduced. Two examples of the detailed messages from each content area are the following:

MILITARY

Three F-1 aircraft from 123-A report sighting 4 small fishing boats and what appeared to be 70 rebel troops on the Northern coast of Monque Island, sector F-8.

In heavy fighting lasting three days 103A has successfully turned back an attack by an estimated two battalions of rebel forces. At least 150 known casualties were inflicted on the poorly organized rebels.

INTELLIGENCE

H.O.M. reports that quality control in his steel products plant has recently deteriorated. He feels that employees sympathetic to the rebels are quietly sabotaging his production process. If UNHS can help him solve this problem, he should show greater cooperation in providing information.

D.N. has learned the enemy negotiating posture may change. He can furnish more details, but in order to pay off his staff of informers and aids, he needs funds as well as recognition that will put him in a favorable light in Savin political circles.

ECONOMIC

It appears that a program initiated by your predecessors to purchase more food-stuffs from the farmers in sector I-4, who are using a new fertilizer provided by UNHS, is beginning to increase the economic prosperity of this region.

An explosion, apparently set off by a team of 15 saboteurs, has destroyed three large tanks of crude oil at the refining facility at Batu. Some piping and pumping facilities were also damaged.

NEGOTIATION

The enemy negotiators have suggested that they may give some ground in the prisoner issue if some of the economic issues are settled in terms acceptable to both sides. The enemy negotiators have shown some interest in offers No. 2 and 7.

Your negotiators report that there is a 50-50 chance that there may be a major break in negotiations within the next few months. Enemy negotiators have been more pleasant and more courteous and appear to have been instructed to take a more accommodating position.

The content analysis proceeded as follows for each of the four status areas. After a process of familiarization with the specific content of all messages and the possible-strategy responses generated by the subjects, four categories of strategies were generated such that they were general enough to include most of the specific responses given by the subject. Actually, one of the categories was of a default nature called the "other" or unspecified category.

Individual attention was then given to each response questionnaire. Each strategy response listed was assigned, as appropriate, to one of the four predesignated categories and the probability associated with the response was added to a cumulative probability pool for that category. For example, suppose a specific response strategy offered within the Economics area was "give aid to farmers in sector H-5" with "50%" listed as the probability that the enemy is indeed employing this strategy. This strategy would be assigned to category 2 (see Table 3-1), namely "Gain Control, Improve Resource Production", and a value of 50 would be added to the probability pool for category 2. After assigning all specific strategies listed by the 16 groups of subjects to one of the four categories and tabulating the probability values, the total accumulated probability within each category was divided by the grand probability total across

TABLE 3-1

MILITARY STATUS

1.	Attack/Control SE Sector	48%
2.	Attack/Control NE Sector	13%
3.	Attack/Control W Sectors	11%
4.	Other	28%

INTELLIGENCE STATUS

1.	Sabotage	33%
2.	Counter Intelligence	8%
3.	Infiltration	23%
4.	Other	36%

ECONOMIC STATUS

1.	Disrupt Trade/Resource Production	23%
2.	Gain Control, Improve Resource Production	41%
3.	Create Black Market	6%
4.	Other	30%

NEGOTIATION STATUS

1.	Negotiate to obtain neutral coalition government (some western influence)	35%
2.	Obtain rebel government by political takeover (reject western influence)	26%
3.	Stall, Deception	16%
4.	Other	23%

all four categories. This process of normalization resulted in an overall percentage figure for each category in a given area (as depicted in Table 3-1). In some cases the subjects' responses were not found to be mutually exclusive or contained two separate strategories in one statement. These problems were handled, respectively, by combining or separating the responses and appropriately normalizing the respective probabilities.

Table 3-1 shows the results of the content analysis. In the military, negotiation and economics areas, a single strategy category was found to predominant over the unspecified or "other" category. In the area of intelligence, the "other" category, containing numerous different strategies -- all of which being quite unlikely, was slightly higher than the highest specific strategy category.

3.3 Task Development

3.3.1 Primary Task. The messages used by O'Connell will be employed in our scenario and implemented as part of a computerized C3 information system. The primary task will be to evaluate incoming messages and to diagnose which strategy the opposition is following. Each message will be displayed as shown in Figure 3-1. Specifically, the player will update, as frequently as he likes, the chances that the opponent is following each of the four possible strategies in the four categories of military, intelligence, economic, and negotiations. Figure 3-2 shows the response format for the operators current evaluation of the opponents strategy, with a sample response vector extended for the military situation.

The content analysis above will be used to select the four strategies in each area. For example, for the "military" situation the four possibilities will be (A) Attack/Control SE sector; (B) Attack/Control NE sector; (C) Attack/Control NW sector; and (D) Attack/Control SW sector.

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ID	SOURCE	CONTENT AREA	SPECIFICITY	RELIABILITY	AGE	# OF TIMES DISPLAYED	MAP UPDATE REQUIRED
J7	G2 BN	POW INT	DETAILED	LOW	2HR	0	YES

J. S. HAS HEARD DISCUSSIONS INDICATING PLANS FOR A MAJOR ENEMY OFFENSIVE SOMEWHERE ALONG THE RAILROAD BETWEEN MCKOSAM AND SAVIN. HE WAS NOT SURE WHERE ENEMY STAGING AREA FOR THIS OPERATION IS, BUT THE EQUIPMENT MOVING ACROSS THE ONDULU RIVER RECENTLY INDICATES IT MIGHT BE THE SWAMP IN SECTOR J-6.

FIGURE 3-1. EXAMPLE OF DETAILED MESSAGE

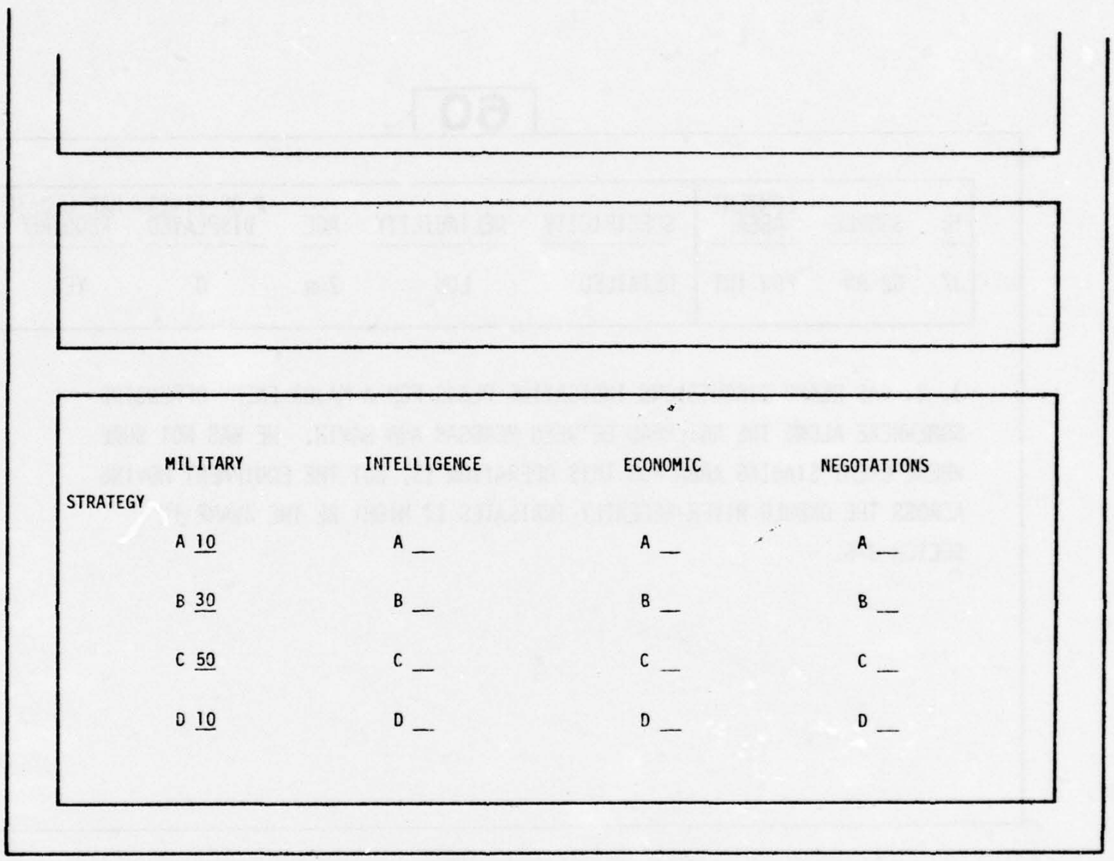


FIGURE 3-2. EXAMPLE OF RESPONSE FORMAT FOR UNCERTAINTY RESPONSES

The player will be constrainted to the four choices selected so that a uniform performance measure may be derived. The players current estimate of the opponent's strategy may be evaluated against the "school" solution by (alternative A in the case of the above example) by utilizing a "proper scoring rule," as described in Section 4.2.1.

3.3.2 Secondary Task. The secondary task involves a paired comparison judgment between headers (i.e., attribute levels) of potentially available messages. Besides serving to dynamically assess primary load, the secondary task simultaneously provides a vehicle for training the adaptive MAU model and keeping it tuned to momentary changes in information preferences. Figure 3-3 shows the display of two sample header vectors of which the operator must choose one. The secondary task procedure and the associated method of performance assessment is detailed in Section 4.2.3.2. The total display configuration combining message display with the primary and secondary task requirements is illustrated in Figure 3-4.

ID	SOURCE	CONTENT AREA	SPECIFICITY	RELIABILITY	AGE	# OF TIMES DISPLAYED	MAP UPDATE REQUIRED
J7	G2 BN	POW INT	DETAILED	LOW	2 HR	0	YES
M1	5 AIR	MTI	SUMMARY	HIGH	1 HR	1	NO

FIGURE 3-3. EXAMPLE OF MESSAGE HEADER CHOICE FOR SECONDARY TASK

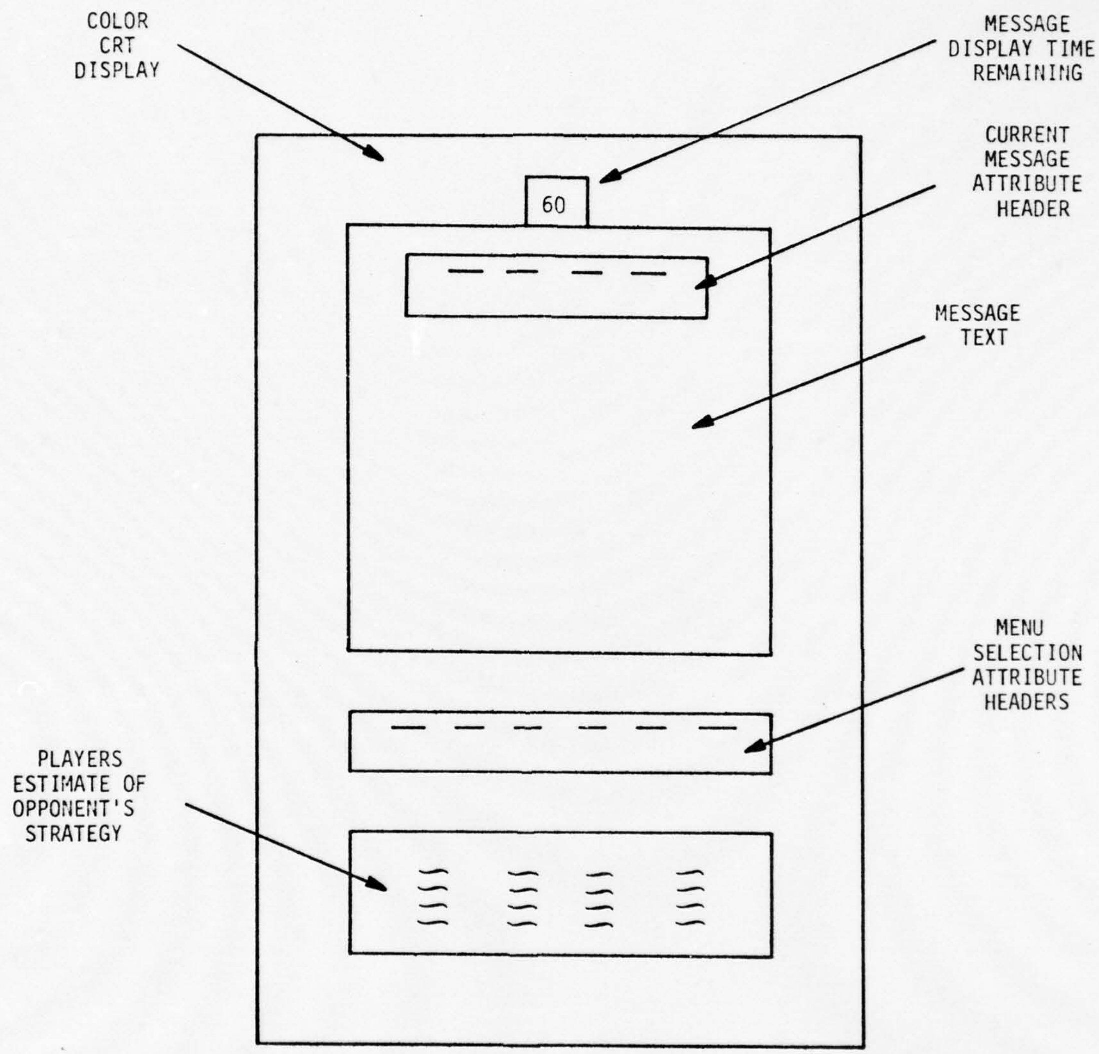


FIGURE 3-4. DISPLAY FORMAT

4. INFORMATION PACING MODEL

4.1 Introduction

This section concerns the model which will be used, within the context of our C3 scenario, to automatically adapt message pacing rate to the information processing and decision making capabilities of an individual operator. The pacing model is based on the implementation of a secondary task to dynamically assess the operator's load on the primary task; in addition, the display time for each message is adjusted with respect to its constituent pacing features. The algorithm adaptively adjusts the pacing rate according to the difference between the actual level of secondary performance and some desired standard or threshold level which is empirically observed, on the average, to be accompanied by the best level of primary task performance. Model-parameter values are determined in a sequence of operator calibration sessions. The functional relationships involved in these sessions are described here and then the dynamics of the pacing algorithm are specified.

Before moving to the technical discussion, it would be worthwhile to summarize the key findings of our planning-and-definition phase of system development.

KEY PLANNING-AND-DEFINITION FINDINGS

(1) It would be most advantageous for an initially developed pacing model to pace one message at a time.

(2) The significance of a message may be related to the relative period of time it should be displayed.

(3) The longer a given message is presented the greater the probability that it will be appropriately attended to and correctly assimilated.

(4) Certain factors which contribute to the importance of, or preference for, a message may be predictive of the length of time required for the operator to process the message.

(5) Before a message is deleted from the screen, the operator should be duly warned and given the opportunity to extend its display life for a limited period.

(6) The secondary task, implemented to dynamically assess primary load, can simultaneously serve as a vehicle to train the adaptive model and keep it tuned to momentary changes in information preferences.

(7) The system should retain some pacing capability even if secondary task performance is not consistently predictive of primary load.

The above principles underlie our system formulation, however several empirical findings drawn from the psychological literature also played a role. Again, by way of preface, these findings are summarized below.

SUPPORTIVE EVIDENCE FOR PACING MODEL

(1) Preferred as well as optimal pacing rates depend upon attributes of the information and environment and vary considerably across individual decision makers (Streufert and Streufert, 1973).

(2) When display load is <u>gradually</u> increased, the performance of highly skilled operators improves with increasing load (Connolly, 1961).

(3) Frequent exposure to a near-saturation task load tends to result in maximum performance levels (Fox and Vance, 1961; Schroder, Driver, and Streufert, 1967).

(4) Under suitable information complexity, pacing in a military allocation task can be speeded up by a factor of from two to three without a significant decrement in decision quality (Hayes, 1964).

(5) Relatively fixed system pacing compared to variable or self-pacing reduces the variability of subjects' output (Boehm, Seven, and Watson, 1971), maintains performance consistency over time (Williges and Streeter, 1972), and improves net performance effectiveness (McFarling and Heimstra, 1975).

(6) Forced "think time" of the appropriate duration contributes positively to performance in a cognitive planning task (Boehm, et al, 1971).

4.2 Operator Pacing Calibration

An essential building block in the pacing model is operator calibration. Calibration proceeds from one stage to the next, and requires an analysis of operator performance under separate conditions where messages are either self-paced (by the operator) or system-paced (by the computer). As described below, the calibration process involves message attributes, primary task performance, and joint primary and secondary task performance when the operator is required to share his time (i.e., cognitive load) between the two tasks. To accomplish all phases of calibration, data will be sampled and analyzed from several experimental subjects.

4.2.1 Measurement of Primary Task Performance. The generalized information selection model and newly developed pacing model will be implemented into a C3 scenario based upon the Tactical and Negotiations Game (TNG), as described in Section 3. The primary task will require the operator to review messages in order to make inferences about the plausibility of specific states of the world (i.e., enemy strategies) concerning specific situations. For each situation, one alternative strategy will be considered the correct one, i.e., the "school solution".

The operator will respond by updating a probability vector across the alternatives within each situation, and he will do so as often as he wishes. Since the school solution is known throughout, the "goodness" of a probability response vector will be determined by the size of the probability placed on the correct alternative (P_c); the "goodness" or update quality (q) measure will be derived from a "proper scoring rule" such as $q_{ij} = S_1 + S_2 \log (P_c + .01)$, where i and j are indices for the particular update and situation, respectively, and S_1 and S_2 are scaling constants. If the operator is required to update a separate probability vector for each of K situations, (e.g., military, intelligence, economic, and negotiation), then the overall measure of performance effectiveness (y) during a task interval will be

$$y = \sum_{i=1}^{K} \sum_{j=1}^{N_k} q_{ij}$$

where N_k is the number of probability vector updates for situation K during the interval.

Thus for example, suppose that an operator is required to update a probability vector for each situational area, that is, military (k=1), intelligence (k=2), economic (k=3), and negotiation (k=4). Suppose further that during the interval he makes 2 military status updates, 1 intelligence status update, 3 economic status updates, and 0 negotiation updates. Then, this total of 6 status updates results in a total of 6 "q" or update quality values which are added up to provide y, a single task performance index across the interval. Therefore, y is a decision (i.e., diagnosis) update quality measure which is a composite of the number of updates per interval and the quality of each respective update, in short, y is a measure of the effectiveness of operator output.

The measure of primary task performance effectiveness has an interesting implication for the MAU model used to select information. The more often the operator updates the probability vectors and the better those vectors reflects his true uncertainty about the respective states of the world, the more timely and better will be the information that is selected for him by the model. The implication results from the fact that the "situation mask" which keeps the model sensitive to the operator's information needs is a function of the uncertainty, $H = -\sum P_i \log P_i$, expressed in each probability vector over i alternatives. For example, if he expresses the desire to be kept well-informed about the military situation yet at the same time shows relatively high uncertainty about this situation, then the relative utility of military information to him will increase. Thus the measure of task effectiveness potentially has both explicit and implicit validity.

4.2.2 Self-Paced Rate and Performance. During Phase 1 of operator calibration, the operator will obtain information in a self-paced mode. The sequence of operations and corresponding output generated in this phase are shown in Figure 4-1. The operator will choose each next message on the basis of header information (Figure 3-3), and he will view each message for as long as he wishes. When desired, he will be able to interrupt the task cycle in order to make a situation-status update. The operator's choices among headers provide data to train the attribute weights for the adaptive information selection model, and to allow for the mean and standard deviation of choice time to be estimated. These data cover items (1) and (4) in the output data list (Figure 4-1). Items (2) and (3) from the list require special explanation which is given below.

4.2.2.1 Message Calibration. For each message displayed to the operator, the computer will keep track of the attribute levels used in the multi-attribute information utility (MAU) computation as well as the actual time the operator perferred to keep the message on the screen. By considering a large number of these self-paced messages, a step-wise linear regression analysis can be performed by considering the attribute levels a_{1i}, a_{2i},

SELF-PACED TASK SEQUENCE

(1) CHOOSE NEXT MESSAGE ON BASIS OF HEADERS
(2) RECEIVE MESSAGE
(3) DELETE MESSAGE
(4) RECEIVE HEADERS (ATTRIBUTE LEVELS) FOR TWO NEW AVAILABLE MESSAGES

OUTPUT DATA

(1) ATTRIBUTE WEIGHTS FOR ADAPTIVE INFORMATION SELECTION MODEL
(2) PREDICTED RELATIVE DEVIATION OF AVERAGE PREFERRED DISPLAY TIME (D) AS A FUNCTION OF A SUBSET OF FACTORS USED IN MAU COMPUTATION (REGRESSION ANALYSIS)
(3) PRIMARY TASK PERFORMANCE (Y) AS A FUNCTION OF AVERAGE PREFERRED DISPLAY TIME (X); SELECTION OF AVERAGE DISPLAY TIME (X_0) RESULTING IN BEST PERFORMANCE
(4) MEAN AND S.D. OF TIME FOR CHOICE BETWEEN HEADERS

FIGURE 4-1. OPERATOR CALIBRATION: PHASE I

a_{3i}, ... of message i as the independent (predictor) variables, and the relative deviation of the message display time (X_i) from some overall mean display time ($\overline{X}$), namely $D_i = (X_i - \overline{X})/\overline{X}$, as the dependent (criterion) variable. $\overline{X}$ might be made equivalent to X_0, which is defined in the subsequent section as the optimal self-paced display time. By pre-establishing a cut-off point for the percentage of variance to be accounted for in the prediction of D_i from the message attribute levels, the equation resulting from the analysis will be of the form

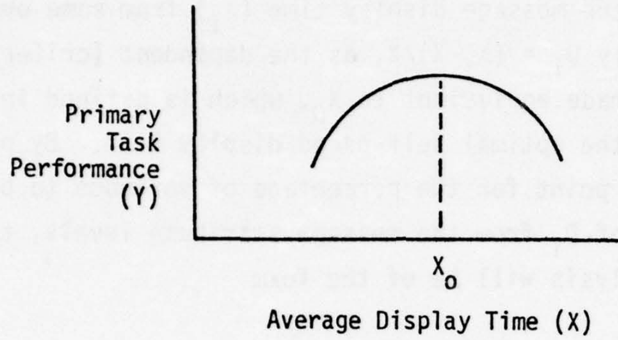
$$D_i = b_1 a'_{1i} + b_2 a'_{2i} + \ldots + C$$

where a'_{1i}, a'_{2i}, ... are the attributes predictive of message pacing; b_1, b_2, ... are the beta coefficients; and c is a constant.

4.2.2.2 Primary Task Performance Under Self-Pacing. The function relating primary task performance to preferred message display time will be constructed as follows. For every set of 10 consecutive messages, the average display time and average level of primary task performance will be computed and plotted against each other on a graph. In accordance with previous research involving the TNG and other tasks, the relationship expected is an inverted-U as shown in Figure 4-2A. From this empirical curve (or any other functional form that results), a point (X_0) will be determined on the abscissa such that $Y = f(X)$ reaches its maximum level at $X = X_0$. As described below in the next stage of calibration, X_0 (i.e., the self-paced preferred message-display time at which primary task performance is best) will serve as a source of selecting different baseline display times for additional calibration under system-paced information presentation.

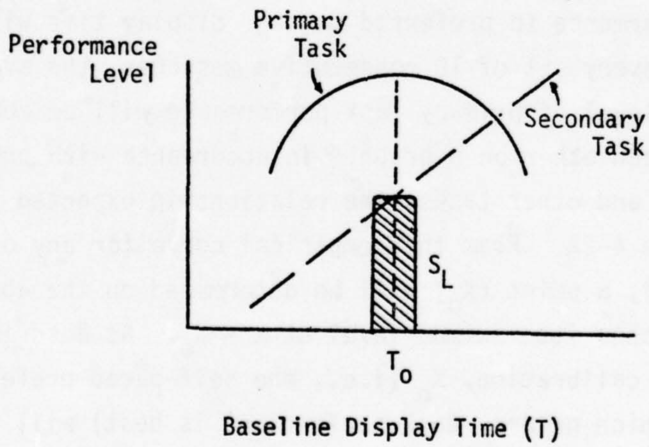
4.2.3 System-Paced Messages and Performance. As outlined in Figure 4-3, the second phase of operation calibration is somewhat more complex than the first phase. Firstly, during Phase II, messages are system-paced

A



PHASE I: CALIBRATION DATA

B



PHASE II: CALIBRATION DATA

FIGURE 4-2. OPERATOR CALIBRATION CURVES

SYSTEM-PACED TASK

PRIMARY TASK

(1) RECEIVE MAU-SELECTED MESSAGES AUTOMATICALLY

(A) AT EACH OF FOUR FIXED BASELINE DISPLAY TIMES DETERMINED BY PHASE I.

(B) WITH THE DISPLAY TIME FOR EACH MESSAGE (i) ADJUSTED BY A COEFFICIENT $(1+D_i)$ AS A FUNCTION OF THE ATTRIBUTES IDENTIFIED BY REGRESSION ANALYSIS.

SECONDARY TASK

(1) RECEIVE HEADERS FOR TWO AVAILABLE MESSAGES AT INTERMITTENT RATE.

(2) MAKE PREFERENCE JUDGMENT BETWEEN MESSAGE HEADERS.

OUTPUT DATA

(1) ATTRIBUTE WEIGHTS FOR ADAPTIVE INFORMATION SELECTION MODEL

(2) RELATIONSHIP OF FIXED BASELINE DISPLAY TIME (T) TO PRIMARY AND SECONDARY TASK PERFORMANCE.

(3) SELECTION FROM (2) OF BASELINE DISPLAY TIME (T_O) CORRESPONDING TO BEST LEVEL OF PRIMARY TASK PERFORMANCE.

(4) SELECTION FROM (2) OF FIXED THRESHOLD PERFORMANCE LEVEL (S_L) ON SECONDARY TASK CORRESPONDING TO BEST LEVEL OF PRIMARY TASK PERFORMANCE (I.E., CORRESPONDING TO T_O).

FIGURE 4-3. OPERATOR CALIBRATION: PHASE II under the control of the computer. Secondly, the secondary task is introduced to dynamically assess operator load with respect to the primary task. Although primary and secondary task performance are assessed simultaneously under system pacing, they are discussed separately for the purposes of clarity.

4.2.3.1 Primary Task Performance Under System Pacing. Operator calibration during Phase II will be built around the value of X_o determined in Phase I calibration (Section 4.2.2.2), i.e., the self-paced preferred message-display time at which primary task performance is best. X_o and its standard deviation (σ) will be used as anchors for generating alternative fixed baseline display times of $X_o - 2\sigma$, $X_o - \sigma$, X_o, and $X_o + \sigma$, whose impact upon performance will be evaluated empirically. Since most of the studies on the effects of information pacing suggest that subjects can work well when forced-paced at rates considerably faster than their own average self-paced rate, the selected values are biased to include two which are below X_o (i.e., faster display times) and only one which is above X_o (i.e., slower display time).

As clarified subsequently in Section 4.3, the baseline display time (T) represents a fixed interval which has not yet been adjusted with respect to D_i computed on the basis of the pacing attributes for message i (Section 4.2.2.1). During Phase II calibration, the message calibration adjustment (determined in Phase I) will be activated. Thus, for example, if T is fixed at 100 seconds, one message might be displayed for 90 seconds and another for 110 seconds depending upon their respective pacing attributes.

The calibration of primary task performance with respect to different baseline display times will be based upon a function relating them to primary task performance. The functional relationship is expected to be similar to the one relating primary task performance to the average self-paced times (Figure 4-2A); however, in the present case, the system-controlled baseline display time (T) will be represented on the abscissa. Again an inverted-U relationship is expected, as depicted by the solid curve in Figure 4-2B. From this curve form (or any other that results), a point (T_0) can be identified on the abscissa such that $Y = f(T)$ reaches its maximum level at $T = T_0$; and T_0 becomes the baseline display time at which primary task performance is best under automated system pacing.

4.2.3.2 <u>Secondary Task Performance Under System Pacing</u>. The secondary task involves a paired comparison judgment between headers (i.e., attribute levels) of potentially available messages. Besides serving to dynamically assess primary load, the secondary task simultaneously provides a vehicle for training the adaptive MAU model and keeping it tuned to momentary changes in information preferences.

During Phase II of calibration (Figure 4-3) the operator will be performing the secondary task concurrently with the primary task. Two sets of message headers (from which he must choose one) will appear on the screen intermittently, i.e., on for R seconds, off for V seconds, on for R seconds, off for V seconds, etc. R and V will be determined on the basis of empirical pilot data including the mean and standard deviation of time for choice between headers calibrated during Phase I (Figure 4-1).

Secondary task performance will be measured in terms of the decision time for the choice among headers, which can range from 1 (i.e., decision made one second after the headers are displayed) to R + 1 (i.e., decision was not made in time -- that is, while headers were displayed). Decision time (DT) will be converted to speed of response by taking the inverse transformation 1/DT. The level of secondary task performance will then be evaluated by taking the average speed of response across a sliding time epoch of standard length (on the order of five minutes) during which the operator is sharing his attention between the primary and secondary task.

For each of the alternative fixed display times (T) (Section 4.2.3.1), the average level of secondary task performance within a standard epoch will be computed. These values will be plotted against T, as shown by the dashed line superimposed upon the previous graph. As T increases (i.e., slower display times), the level of secondary task performance is expected to steadily increase. By examining the primary and secondary task performance level curves in combination, a fixed standard threshold level of secondary task performance (S_L) can be determined. S_L is the level of secondary task performance at which primary task performance reaches its best level under system pacing. It is assumed, therefore, that as long as an operator maintains this threshold level of secondary task performance (within the standard time epoch), he can perform the primary task well at his own pacing capability. In other words, the message pacing rate for an operator will be adaptively adjusted in accordance with how his level of secondary task performance deviates from S_L. Thus, the varied total capabilities of different operators can be conceptualized as shown in Figure 4.4.

4.3 Pacing Algorithm

In the automatically paced information presentation system, a single pacing algorithm is used to compute the display time for each message before it is presented on the screen. The algorithm has two basic components. The first component involves a baseline display time which is adaptively adjusted in accordance with gradual changes in operator response to task demands as measured by secondary task performance. The adjustment process is accomplished reiteratively across a moving window of task performance of fixed duration, on the order of five minutes. The second component is a linear function of specific features of the particular message to be displayed.

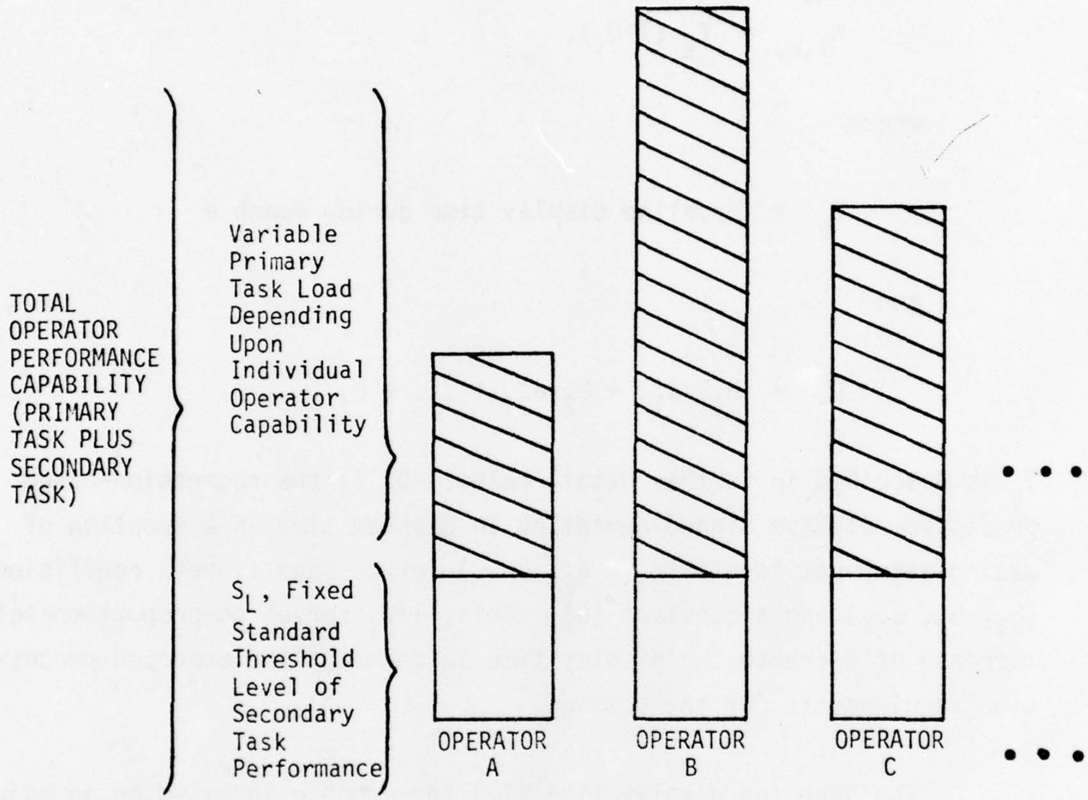


FIGURE 4-4. CONCEPTUALIZATION OF VARIED OPERATOR CAPABILITIES

The two components are combined multiplicatively to determine the display time ($M_{i,e}$) for message during epoch (i.e., window) e:

$$M_{i,e} = T_e (1+D_i),$$

where

$$T_e = \text{baseline display time during epoch e}$$

and

$$D_i = b_1 \; a'_{1i} + b_2 \; a'_{2i} + \ldots + c,$$

T_e is described in further detail below. D_i is the regression-based predicted relative signed-deviation in display time as a function of pacing-attribute levels (a'_{1i}, a'_{2i}, ...) for message i, beta coefficients (b_1, b_2, ...) and a constant (c). This, $1+D_i$ serves to proportionately increase or decrease the display time in terms of the expected processing time requirements for the message.

The baseline display time (T_e) for epoch e is based on an adjustment to the operator's baseline display time during the previous epoch (T_{e-1}) in accordance with his level of primary task load as inferred from his secondary task performance during that epoch. At the start of a system based session, the baseline display time will be initialized at the previously calibrated level of T_o. The adaptive equation is:

$$T_e = T_{e-1} + (S_{A,e-1} - S_L) \cdot \Delta,$$

where

$S_{A,e-1}$ = Level of actual secondary task performance during epoch e-1;

S_L = Fixed threshold level of secondary task performance within an epoch, calibrated in accordance with best average primary task performance;

Δ = Adaptive increment (i.e., sensitivity coefficient determining the amount of change in T per unit difference between $S_{A,e-1}$ and S_L).

The parameters S_L and Δ will be determined by operator calibration (as described above) and preliminary empirical tests using the pacing system, respectively.

4.4 System Process Description

Figure 4-5 shows the major components of the information selection and pacing system in block diagram form. These components can perhaps be most easily described in terms of their impact upon each other.

The scenario-generated "Message Universe" leaks messages into an "Available Ranked Messages" store according to some time-dependent distribution (e.g., Poisson). This process mirrors the situation in the real world where messages generated from the external environment in real time are not available for display until they have been stored in a computer data base. In addition, the timed message inflow allows for message age (from time of availability) to be computed and used as an attribute of the message which is likely to affect operator information preferences.

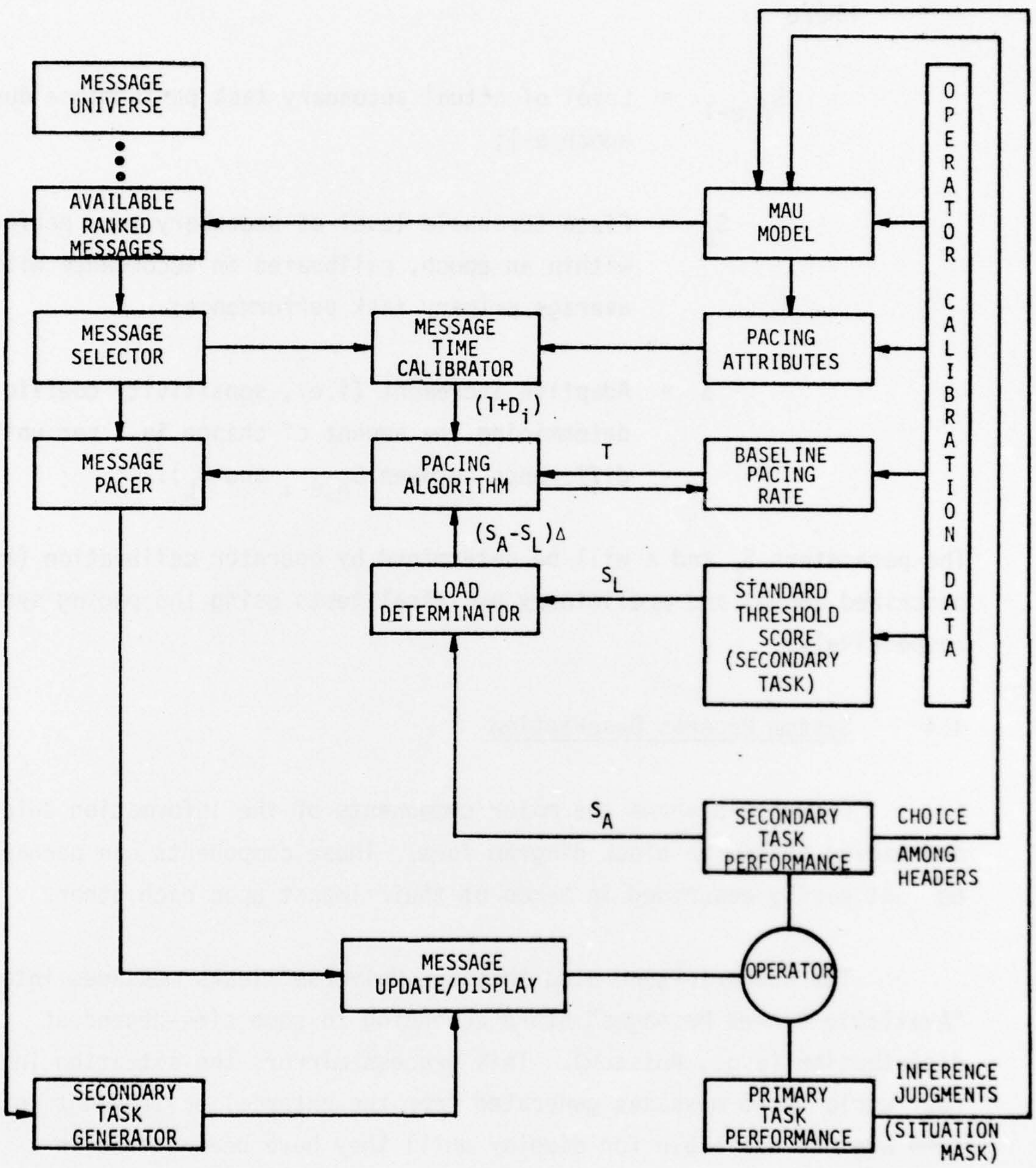


FIGURE 4-5. INFORMATION SELECTION AND PACING MODEL

The messages in the available store will be continuously maintained in rank order according to their aggregate multi-attribute information utility (MAU) value. The computation of MAU will be determined by the "MAU Model" whose input includes the attribute importance weights previously calibrated for the operator (i.e., attribute weight vector), the respective attributes levels assigned to each message (i.e., source characteristic vector), and a quantitative specification relating to immediate situational needs (i.e., situation mask vector). Thus, the available information store represents a queue of messages whose MAU ranks are continuously updated, i.e., whenever a new message enters or, if desired, whenever the environmental situation (situation mask vector) changes.

Messages are pulled from the available message store and displayed to the operator by the "Message Selector" and "Message Pacer". The pacer will take advantage of a "Pacing Algorithm" designed to maximize message throughput. The algorithm is directly dependent upon multiple components. First, there is the initial "Baseline Pacing Rate" for the operator which is determined from previously collected calibration data. This baseline rate is then adjusted by the algorithm in two separate ways: In the short-term, a message-by-message adjustment is made by the "Message Time Calibration" unit. This calibration utilizes the level of specific attributes of each particular message to predict how much its display time should be increased or decreased over a desired overall average message display time. On a more long-term basis (say every five minutes), the pacing algorithm adjusts the baseline display time within a given time epoch as a function of operator load during the previous epoch. The adjustment is carried out by the "Load Determinator", which measures load on the primary task by comparing, across the previous epoch, the operator's actual performance on the secondary task with a "Standard Threshold Score." The threshold score is fixed at a desirable level predetermined in calibration sessions to be accompanied, on the average, with the highest level of primary task performance. Thus, "Operator Calibration Data" serves as an important contributory component to the pacing procedure.

The "Operator" performs the primary task and secondary task concurrently. The successive messages (i.e., primary information) and message header selections (i.e., secondary information) presented to the operator on his "Message/Update Display" both originate from the "Available Ranked Messages" store. The message header selections are produced by the "Secondary Task Generator". The decisions or choices among headers resulting from "Secondary Task Performance" play a role in updating the "MAU Model". Similarly, the "MAU Model" is dynamically affected by the inference judgments which make up "Primary Task Performance".

5. SOFTWARE DEVELOPMENT

5.1 System Configuration

The system configuration involves an operator employing a simple function-oriented input device while viewing information on a high-resolution 19" color monitor. In addition, the experimenter and observers can view the system's operation in a separate room using the Advent group display monitor. The entire configuration is shown in Figure 5-1.

The software supporting this system features a multi-process, asynchronous environment in which the following activities are managed:

(1) control process
(2) primary task process
(3) secondary task process
(4) display-clock process
(5) input process
(6) graphics process

The operating system employed, UNIX, supports the development of this type of real-time command and control program. Figure 5-2 shows the software configuration. Each of the six processes are described below.

5.1.1 Control Process. The control process regulates the operation of the system in the following manner:

(1) The experimenter may communicate through it to define system variables and control experiments.

(2) Experimental data is recorded.

(3) Experimental results are analyzed and printed.

5.1.2 Input Process. During the input process, input from the operator's entry terminal is handled. If priority inputs are present, immediate display updates are performed.

5.1.3 Primary Task Process. The primary task process generates new messages, adds them to the pool of available messages, and selects a message for display from those available. The multi-attribute model is also updated during this process.

5.1.4 Secondary Task Process. The secondary task process selects and displays a new pair of message-attribute vectors. Performance data are recorded with respect to the operator's behavior in choosing between these vectors.

5.1.5 Display-Clock Process. The display-clock process updates the message-time-remaining counter on the display and initiates a flashing alert signal when the messate-time-on-screens exceeds a threshold value.

5.1.6 Graphics Process. The graphics module interfaces between the PDP 11/45 and the GENISCO graphics system. The physical updating and formatting of the display take place here.

5.1.7 Primary Software Development Tasks. The following tasks must be performed in developing the necessary software:

(1) Definition and design of system processes.
(2) Design of principle file and data structures.
(3) Detailed design of algorithms.
(4) Design of graphics support structure.
(5) Coding of detailed design.
(6) Checkout and integration of software components.

A preliminary information diagram describing process data flow for the operational system is summarized in Figure 5-3.

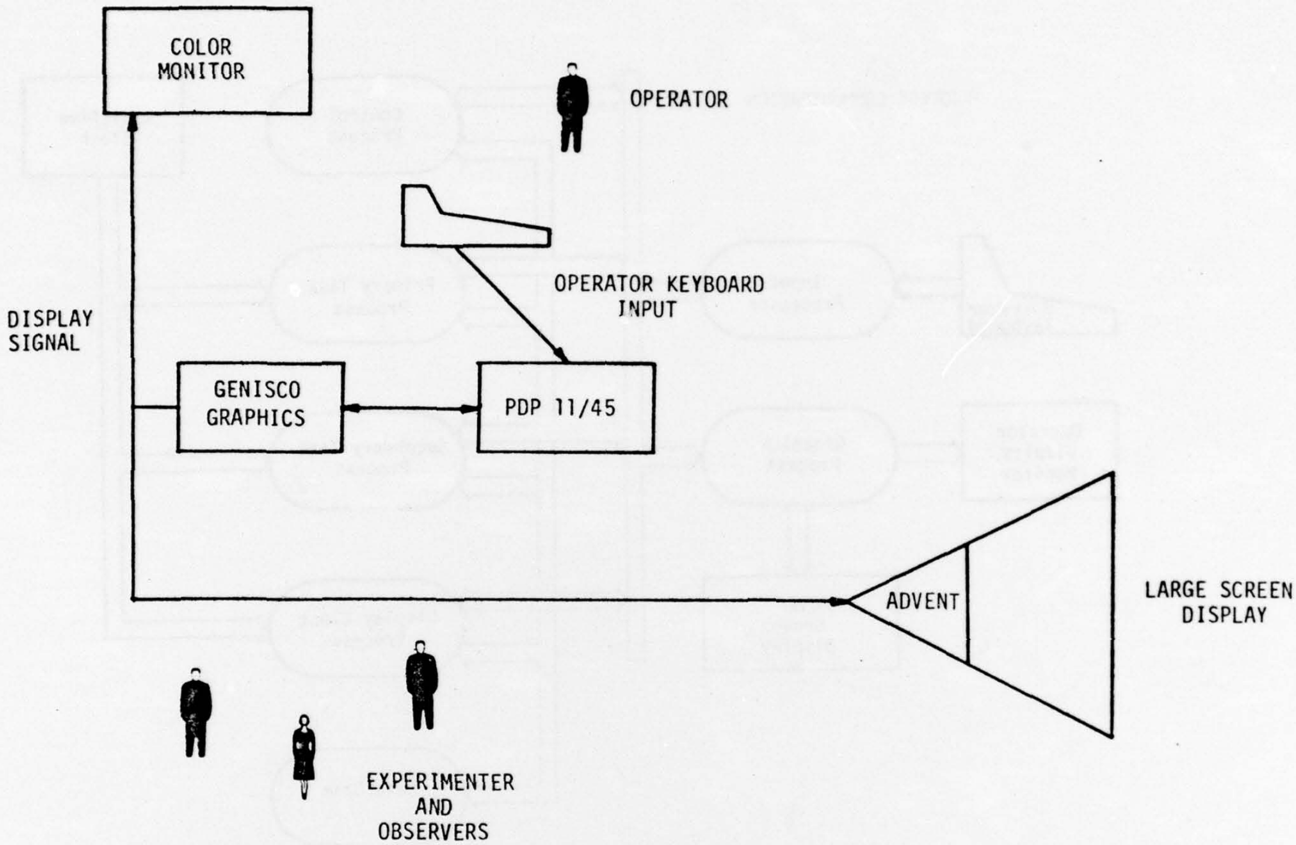


FIGURE 5-1. SYSTEM CONFIGURATION

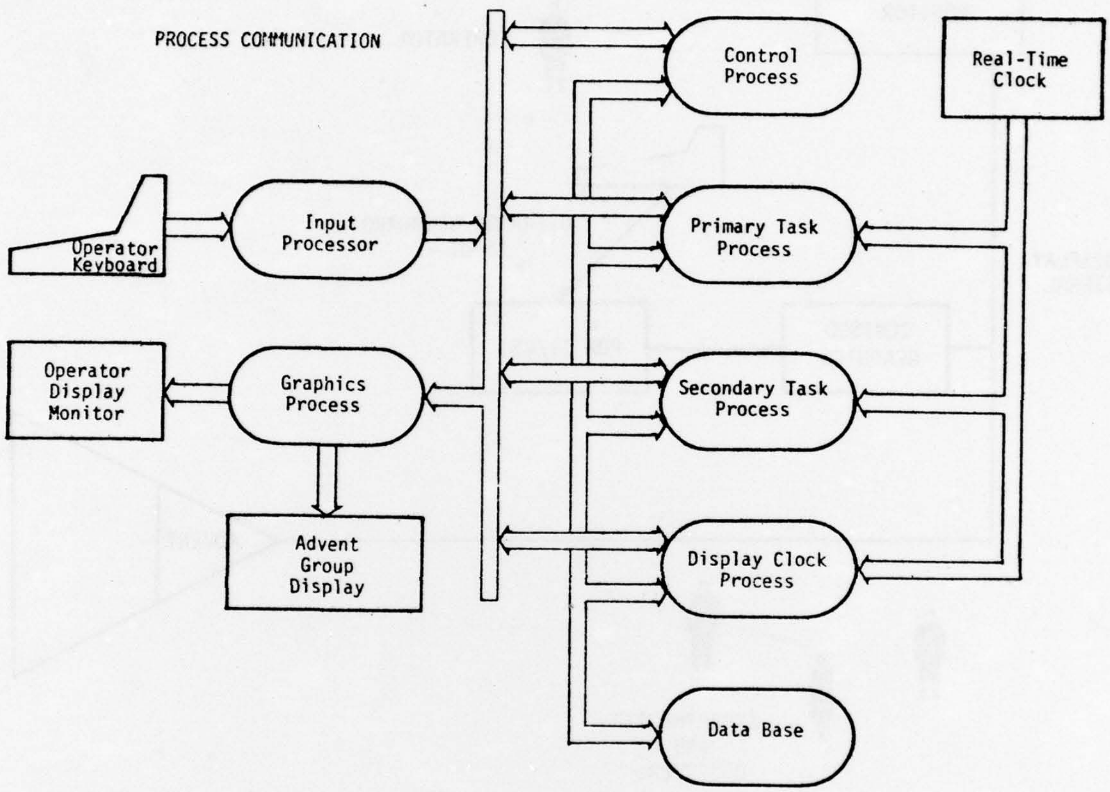


FIGURE 5-2. SOFTWARE CONFIGURATION

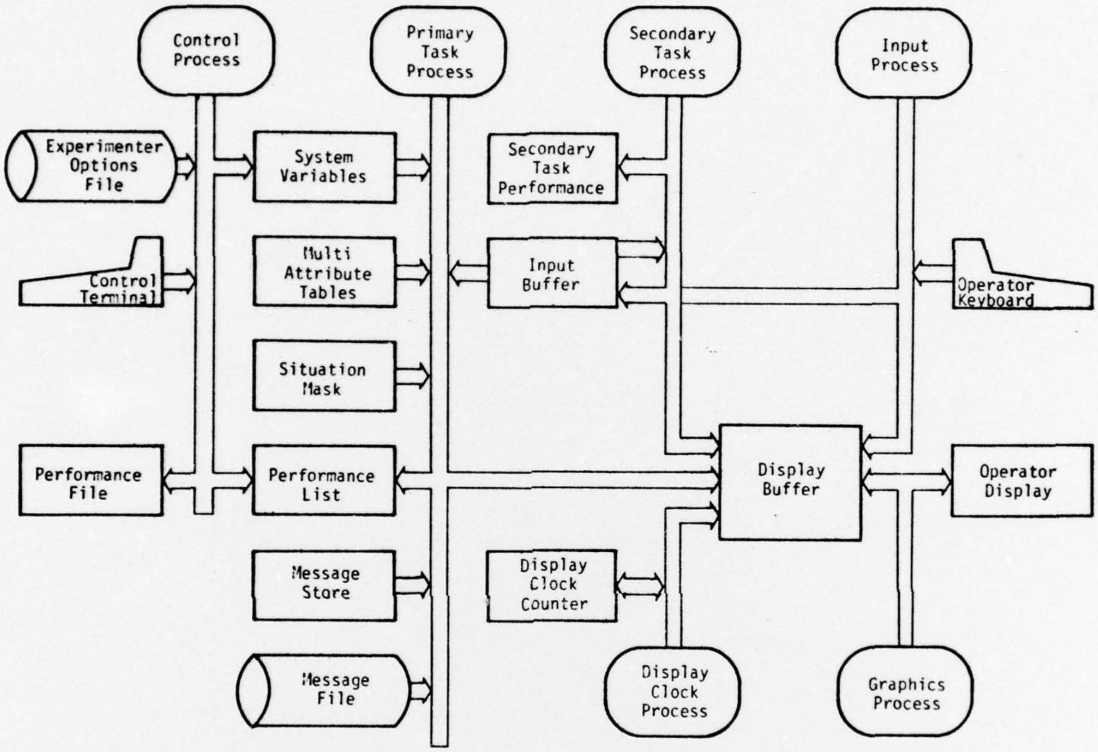


FIGURE 5-3. PROCESSES DATA FLOW

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